Fabrication Technology for Monolithic Integration of Film Bulk Acoustic Wave Resonator on CMOS Circuit

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論 文 内 容 要 旨

To utilize the performance of mechanical devices, the fabrication conceptual ideas are important for integrating such devices with CMOS integrated circuit (IC). There are already many developed researches available for integrating CMOS IC and mechanical devices. Among these, most popular technologies are system-on-chip (SoC) and system-in-package (SiP). SoC is classified for the integration of digital, analog and mixed signal systems which are fabricated on a single substrate. In early 2000s the start of system-on-chip introduced many additional advantages for applications like wireless sensor network (WSN), radio-on-chip, microcontrollers, etc. The commercial products under SoC development now can be easily seen in 1) Apple's A5 processor which includes image signal processor, random access memory (RAM) module with their Cortex-A9 microprocessor core for smartphone applications; 2) Nvidia's Tegra 2 SoC which has video decode processor, audio processor, image signal processor, graphics processor, universal serial bus (USB) controller, etc for tablet applications; 3) implantable medical devices and many more. But development of SoC is limited to only CMOS level and more research are in progress to develop machines on chip (MoC). SiP involves different devices developed and fabricated on individual substrates and packaged with necessary requirements according to the application. Huge memory module, complex logic, analog or mixed signal chips, radio frequency (RF) chips, passives fabricated on state-of-the-art lossless substrates, discrete micro-electromechanical systems (MEMS), optical setups, etc. are possible to be utilized for making full system in one packaged module. However, these are in research and need further investigation especially in the performance and reduction in power as a full system. At present, combo sensors use SiP approach where multiple sensors like accelerometers, gyroscopes are integrated in a single package. But, further miniaturization by SiP approach is difficult. Also, it is difficult to integrate many mechanical, optical, etc. elements just in a manner of wafer-bonding i.e. stacking method. Monolithic approach of integration has advantage of area compactness, low interconnection parasitics and cost reduction. But one has to limit to structural materials to be used in such approach which are

compatible with CMOS circuit. Hence, the future direction must include combination of monolithic, wafer-bonding-based and SiP approaches.

This thesis work proposes the method of developing an adhesive-film-based thin film transfer technology for monolithic integration of thin film bulk acoustic resonator (FBAR) based CMOS voltage controlled oscillator (VCO). The flexibility of this process is that such thin film could be any of the following: crystalline Si, SiC, and diamond. For this process, the single crystalline silicon is utilized as a sacrificial layer for air gap type FBAR. Aluminum nitride is utilized for demonstrating such process as it is very promising piezoelectric material which already showed great performance characteristics for many discrete devices. And hence the proposed process is developed so that it can be extended to all those discrete mechanical devices utilizing aluminum nitride film on transferred thin film. This work utilized three different CMOS integrated oscillator circuit fabricated in 0.18 μm TSMC RF process technology and 0.18 um TSMC CIS process technology. The CMOS IC is prepared for MEMS integration by sputtering Au-Cr metal over TSMC's metal 6 (M6) pad areas. This is performed for two main reasons 1) prove any change in FBAR performance over the transistor area and 2) protect the aluminum pad areas during plasma etching process. The silicon-on-insulator (SOI) chip is utilized for transferring its thin film silicon device layer on the CMOS chip. A thin adhesive polymer benzocyclobutene (BCB) is used as a bonding material for bonding these two chips. For this process as low as 1 μm of BCB was developed for successful and uniform film transfer. Later, the handle silicon layer is etched down to the BOX layer of SOI chip and BOX layer is removed by wet etching. The FBAR structure which follows basic fabrication technologies of deposition, photolithography, etching, etc. is fabricated. The most required specification for fabricating FBAR structure is the flatness of the bottom layer. Hence, the uniform and flat silicon transfer is necessary which shows important and constructive theme for this integration process. Aluminum nitride is used as a piezoelectric material sandwiched between ruthenium and aluminum metal electrodes for bulk acoustic wave (BAW) resonator. For interconnecting the FBAR electrodes and metal pads of CMOS IC, silicon and BCB etching is performed by switching the gas combination and utilizing same photoresist pattern. Finally, the silicon layer underneath the active area is sacrificially etched to make an air gap type FBAR.

For the above fabrication process, the pierce and inverter based FBAR digital controlled oscillator (DCO) circuit is designed. The comparison with other published works showed better Figure of Merit (FoM). And for successful oscillation, the choice of maximum motional resistance value in FBAR is necessary. In addition to FBAR-DCO design, a 1.9 GHz cross-coupled FBAR-based VCO is also designed. Due to low frequency instability in differential oscillator, a novel optimization method is investigated for avoiding parasitic oscillation. The pierce based FBAR-DCO is fabricated in TSMC 0.18 μm RF process technology. The inverter based FBAR-DCO and 1.9 GHz cross-coupled FBAR-based VCO are fabricated in TSMC 0.18 μm CIS process technology.

As aluminum nitride is utilized as a piezoelectric material, the study is made for good c-axis oriented film by different sputtering method. ECR sputter, RF sputtering and AC reactive magnetron sputtering units were studied. Due to the non-repeatability and plasma instability, ECR sputter didn't produce same results for consequent sputtering. The optimum stress and rocking curve FWHM was provided by RF sputtering unit. But in addition to fabrication process, such quality of film didn't showed good FBAR characteristics. Later, an AC reactive sputtering unit was utilized and studied for sputtering on 20 cm square samples. A rocking curve FWHM value of as good as 1.6° is obtained on Ru/AlN/Si/BCB/LSI layers.

The fabrication issues occurred and successfully solved during the process development are: 1) etch selectivity of BCB vs. silicon dioxide/aluminum, 2) aluminum nitride orientation and stress problem, 3) patterning issues for aluminum nitride, aluminum and Au-Cr metals as positive developer damages aluminum nitride film, and 4) photoresist silylation problem due to improper HMDS treatment resulting as a mass load on FBAR for damped resonance.

In conclusion, an adhesive-film-based thin film transfer technology for monolithic integration of FBAR based CMOS VCO is successfully completed. After overcoming the above mentioned issues, the standalone resonator devices were characterized and compared with devices fabricated on SOI chip. The comparison showed significant effect of pad parasitic. Apart from the pad parasitic values, the impedance value at parallel resonant frequency for both the chips are different. This difference is as minimum as 300 Ω. For working oscillation, the impedance at parallel resonant frequency should be ~1200 Ω. As such value was not obtained for resonator devices on SOI chip, the quality of aluminum nitride film in addition to other related issues need to be studied further.

論文審査結果の要旨

ネットワーク型小形センサ等に高速通信機能や高性能アナログーデジタル変換機能を内蔵するためには，集積回路上に高性能のクロック共振子をモノリシックに集積化する必要がある。高性能のクロック共振子は，機械振動特性に優れる材料で作製されるべきであるが，特に数百 MHz 以上の高周波領域では，圧電材料である窒化アルミニウム（AlN）薄膜がそのための優れた材料の 1 つである。高性能 AlN 薄膜を集積回路上で利用するためには，集積回路表面の構造や表面粗さが AlN 成膜に与える影響を抑え，同時に AlN 成膜が集積回路に与える損傷を抑えなくてはならない。さらに，実用的な観点からは，AlN 共振子の作製プロセスは，半導体ファウンドリで製造される標準的な CMOS（Complementary Metal-Oxide Semiconductor）回路にそのまま適用できるものでなくてはならない。

本論文は，上述の課題に対して，単結晶 Si の薄板を別の基板から集積回路基板に樹脂接合によって移設し，これによって平坦化された同基板上に AlN 薄膜バルク音響波共振子を集積化するための方法を提案し，そのための要素加工技術を開発し，最終的に試作デバイスを得るに至った成果をまとめたものであり，全編 5 章からなる。

第 1 章は序論であり，研究の背景としてクロック共振子のモノリシック集積化の必要性，技術的課題などが参考文献を引用しながら論じられた後，研究の目的が述べられている。

第 2 章では，AlN 薄膜バルク音響波共振子の設計，およびそれを用いた 2 種類の電圧制御発振器（Voltage Controlled Oscillator，VCO）の設計が述べられている。低い位相ノイズを得るための VCO の構成が提案され，AlN 薄膜バルク音響波共振子の等価回路を用いて発振回路の動作がシミュレーションされている。その結果，従来より高い性能が期待される設計が得られ，シャトルサービスによる集積回路の試作に供されている。これは有用な成果である。

第 3 章では，高性能 AlN の低温スパッタ堆積技術が述べられている。集積回路上の薄膜バルク音響波共振子に AlN 薄膜を適用するためには，c 軸配向性に優れる薄膜を，350℃程度以下の成膜温度で，しかも応力を抑えて堆積する必要がある。3 種類のスパッタ成膜法，具体的には，ECR（Electron Cyclotron Resonance）プラズマスパッタ法，高周波マグネトロンスパッタ成膜法，および 2 カソード間交流スパッタ成膜法が試みられ，3 番目の方法によって 350℃程度の低温で良好な AlN 薄膜が得られている。20 mm 角の小片基板上に成膜するための方法，およびそのときの成膜特性についても研究されている。ここで実証された成膜法は，費用の観点から小片基板上に試作せざるをえない CMOS 集積化 AlN デバイスの開発に必要であり，重要かつ有用な知見である。

第 4 章では，AlN 薄膜バルク音響波共振子を CMOS 回路上に集積化するための加工技術について述べられている。半導体ファウンドリから納品された集積回路基板の表面処理技術，単結晶 Si の薄板を別の基板から集積回路基板に樹脂接合によって移設する技術，AlN 薄膜のエッチング技術，Si 犠牲層エッチング技術などの要素加工技術が開発され，最終的に AlN 薄膜バルク音響波共振子を用いた VCO が試作されている。また，試作されたデバイスの評価も行われている。ここで開発された加工技術は，AlN 薄膜バルク音響波共振子だけではなく，様々な集積デバイスに適用できるものであり，重要かつ有用な成果である。

第 5 章は結論である。

以上，本論文は，CMOS 回路上に AlN 薄膜バルク音響波共振子をモノリシック集積化するための新しい方法を提案し，そのための要素加工技術を開発し，さらに，従来より高い性能が期待される VCO 回路を設計し，これらを総合して，CMOS 回路上に AlN 薄膜バルク音響波共振子を実際に試作した結果をまとめたものであり，ナノメカニクスとマイクロマシン工学に寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として合格と認める。